E. Moyo et al. Int. Journal of Engineering Research and Applications www.ijera.com
ISSN: 2248-9622, Vol. 5, Issue 7, (Part - 4) July 2015, pp.07-12

RESEARCH ARTICLE OPEN ACCESS

Modeling and Analysis of Wholesale Competitive Electricity Markets: A Case For Zambia

E. Moyo, B. R. Pokhrel and B. Adhikary
Kathmandu University, Nepal

Abstract-
Electricity markets all over the world are moving towards greater reliance on competition and this has become a global trend as a method of best practice. However, before competition is introduced in electricity markets it is imperative to model and assess the behavior of the market. The assessment includes calculating the market performance indices to determine the levels of market power exploitation by the Generating Companies (GenCos) that will participate in the market. This paper presents a study on modeling and analysis of wholesale competitive electricity market for a developing country to help regulators assess and predict market behaviour. It involves modeling and simulation of the Zambian power system network in Agent-Based Modeling of Electricity Systems (AMES) using real system data to pick out critical information that enables us to assess the status of the market. The results indicate that market power exploitation is prevalent for the two largest GenCos assessed.

Keywords: AMES, DCOPF, Locational Marginal Prices (LMPs), Residual Supply Index (RSI), Lerner Index (LI), Relative Market Advantage Index (RMAI), Zambian Power Network.

I. INTRODUCTION

Restructuring in developing countries is still at its infancy stage and is mainly driven as a part of government's macroeconomic policy to encourage privatization and investments mainly in the generation sector. Furthermore, the increase in power demand has also enhanced some private sector interest to invest in the power sector. It has been observed through working electricity markets and research that workable competitive electricity market can drive this investment and reduce prices by introducing cheaper generation technologies in the network. In a competitive market environment, infrastructure additions (Generation, Transmission and Distribution equipment etc) are a result of investment by independent companies seeking profit from their investments.

In developing countries however, there are no market operators and new generation investments is driven mainly through signed Power Purchase Agreements (PPAs).

The electricity supply in Zambia can best be described as an oligopoly with the presence of Lunsemfwa Hydro Power Company (LHPC, 52.5MW) an Independent Power Producer (IPP) and Copperbelt Energy Corporation (CEC) an independent transmission company on the Copperbelt province. It is dominated by the state owned utility, Zesco with generation, transmission and distribution business units. The grid connected generation is hydro based which include Kafue Gorge Power Station (KGPS, 990MW), Kariba North Bank Power Station (KNBPS, 720MW), Victoria Falls Power Station (VFPS, 108MW) and four small hydros in the northern part of the country with a total capacity of 23.75MW.

II. MARKET PERFORMANCE MEASURES

According to [1] and [2] market concentration is the extent to which a relatively large share of market activity is carried out by a relatively small number of participant firms. The intuitive idea is that anticompetitive behavior by firms is to be expected in a market that is highly concentrated. Market concentration measures are most often applied to the seller side of a market. These measures depend critically on the number of firms selling into a market; and the relative "market share" of these seller firms as measured either by output, by sales revenues, or by operating capacity.

All else equal, these measures indicate an increase in concentration either when the number of firms decreases or when the market share of the largest firms increases. The market concentration measures used in this study include the Lerner Index (LI), Residual Supply Index (RSI) and the Relative Market Advantage Index (RMAI). Detailed formulas and description of these concentration measures can be found in [1].

III. AMES TEST BED SOFTWARE

AMES (Agent-based Modeling of Electricity Systems) is an open-source agent-based computational laboratory designed for the systematic study of restructured wholesale power markets operating over AC transmission grids subject to congestion. Hourly Locational Marginal Prices (LMPs) for the day-ahead market are determined via DC Optimal Power Flow (DCOPF) based on the demand bids and supply offers of traders with learning capabilities. AMES incorporates, in simplified form, core features of the wholesale power market design proposed by the U.S. FERC. A detailed description of AMES and its features can be found in [3] [4] [5] [6] [7] [8] and [9].

IV. MODELING AND SIMULATION OF THE ZAMBIAN NETWORK IN AMES

In the study the objective is to minimize generator total variable costs in (1) subject to power-flow balance constraints, transmission branch limits, and GenCo capacity constraints.

$$\text{Min} \sum_{i=1}^{I}[aP_{Gi} + bP_{Gi}^{2}] + \pi[\sum_{km\in BR}[\delta_k - \delta_m]^2] \tag{1}$$

A 33 bus system high voltage network of the Zambian system was modeled with grid connected generating stations. In the study seven GenCos were considered with VFPS modeled as three different companies comprising VFPS A, VFPS B and VFPS C, others include KGPS, KNBPS, LHPC and the small hydro power stations in the northern part of the country were grouped together to form one company called SmallHydros. Fourteen Load Serving Entities (LSEs) were selected as bulk supply points. The cost functions determined in [10] are used in this study and are given in Table 1.

Table 1: Cost Functions used in the Study

Power Station	**Cost function coefficients**	
	a($/MWh)	**b($/MW^{2}h)**
KGPS	**0.465240492**	**0.00004348**
KNBPS	**1.127592221**	**0.000579739**
VFPS A = SmallHydros	**1.032842787**	**0.085033729**
VFPS B = VFPS C = LHPC	**0.756703828**	**0.000145758**

The simulation can be controlled to run for a specified number of days. In this case, weekly load simulations were conducted for a 100 day period to depict one season loads on the assumption that the change in the load profile between weeks and/or months during a season is minimal or negligible

The cases that were modeled include a single buyer model (base case) and a wholesale model (contract case). The study considered RSI, LI and RMAI calculations to determine market power abuse and the effects of constrained generation on profits and LMPs for the two largest power stations for the above mentioned cases. The study also considered the RSI calculation for the forecasted generation and demand for the year 2020.

V. RESULTS AND DISCUSSION

A. Base Case

The RSI results for the two largest GenCos, KGPS and KNBPS are given in Table 2. It can be observed that none of the GenCos has an RSI value that is above 1. This means that the two GenCos are exhibiting potential seller market power because total demand cannot be met without their capacity. KGPS exhibits the worst RSI result.

The Results of the RMAI from day 5 to day 100 on a 5 day incremental basis are shown in Fig. 1 and Fig. 2. The RMAI values for both GenCos are greater than 0, a necessary condition for the GenCos to exercise market power. However, in this case KNBPS exhibit the worst RMAI result.

The results of the LI, also calculated from day 5 to day 100 on a 5 day incremental basis at hour 19, are shown in Fig. 3 and Fig. 4 for KGPS and KNBPS respectively. The LI values for both GenCos are greater than 0, a condition necessary for the GenCos to exercise market power during the time period. In this case, however, the LI results agree with the RSI.

B. Contract Case

The RSI results for the two largest GenCos, KGPS and KNBPS are given in Table 3. It can be observed that the RSI values have improved compared to the base case; however KGPS is still exhibiting potential for seller market power. KNBPS exhibits potential for seller market power during the peak period only, however if we use the rule that RSI should be greater than 1.1 ninety-five percent of the time then KNBPS does not meet the criteria based on 24 hours for the entire simulated season.

The RMAI values for both GenCos are worse off compared to the base case. In this case KNBPS exhibit very high levels of market power. This result does not agree with the RSI results. This is because there is a huge variation in the GenCo profits benchmark for the contract case and this forms the basis for the RMAI calculation.

The LI values show fluctuations between the first day and day 55 for both GenCos and are slightly worse off compared to the base case. This is because a significant amount of supply has been taken out of the market which results in rise in prices as exhibited by the LMPs. This result is expected since the LI is calculated with reference to the true marginal costs which are the same for both the contract and the base case.

C. RSI Forecasted Generation Case

The RSI was calculated based on the lower, base and upper forecasted peak demand for the supply that is due to be completed by 2020. The RSI results for the four largest GenCos, KGPS, KNBPS, KGL and Mamba are given in Table 4. It can be observed that the RSI values are above 1 for the lower and base peak demand scenarios. Since these peak demand values represent peaks in the year 2020, it can be inferred that all GenCos except KGPS will have RSI values greater than 1.1 for 95% of the time in 2020 for the lower and base peak demand scenarios. From this result we can predict that the market is moving towards a situation where abuse of market power won't be prevalent. However it should be noted that RSI does not take into consideration the complexities of physical network architecture that could possibly give otherwise results.

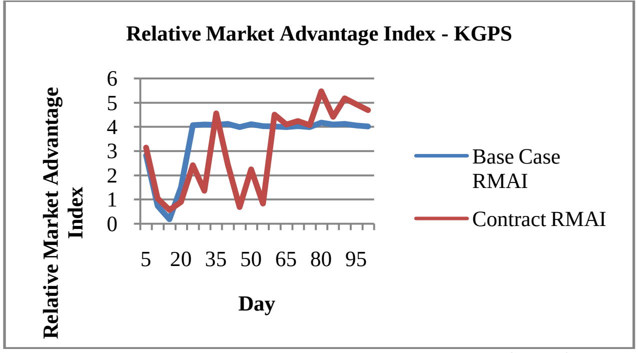

Figure 1: Relative Market Advantage Index Trend for Kafue Gorge Power Station (KGPS)

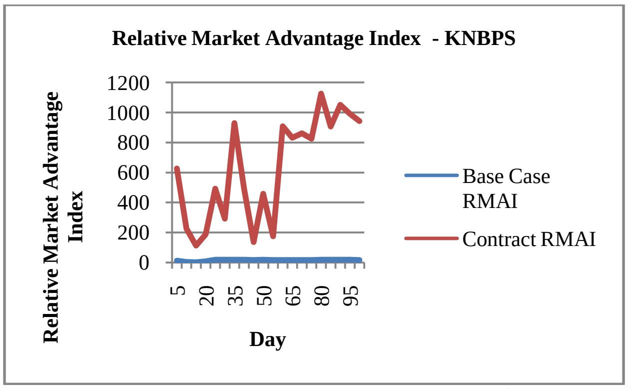

Figure 2: Relative Market Advantage Index Trend for Kariba North Bank Power Station (KNBPS)

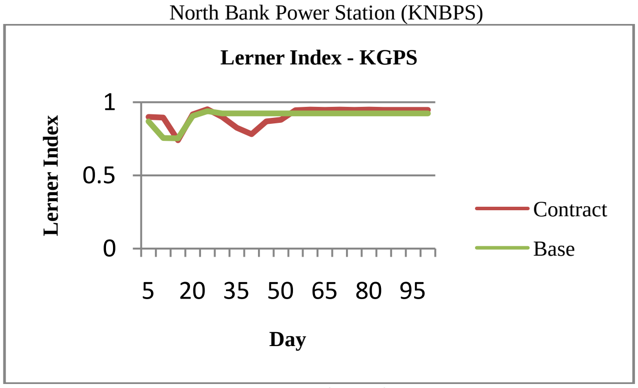

Figure 3: Lerner Index Trend for Kafue Gorge Power Station (KGPS)

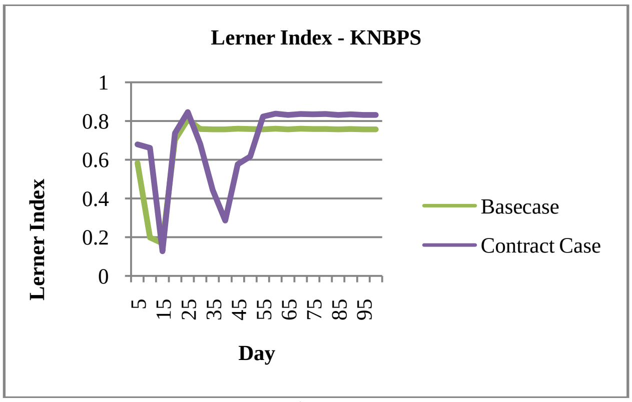

Figure 4: Lerner Index Trend for Kariba North Bank Power Station (KNBPS)

D. Comparison of Profits and LMPs under Constrained Conditions

Fig. 5 shows the effect on the profits for KGPS under the different scenarios. It can be observed that KGPS would earn the highest profits when KNBPS is constrained during the base case and it would earn the lowest profits on the average when it is unconstrained during the contract case. When KGPS is constrained both under the base and contract case it is substantially earning reasonably high profits compared to the unconstrained base and contract cases respectively. This can give KGPS incentives to strategically withhold output in order to raise its profits. The market regulator, Energy Regulation Board (ERB) of Zambia would therefore be required to assess the true status of the GenCo under these scenarios.

On the other hand, KNBPS would earn the highest profits when KGPS is constrained under the contract case and it would earn the lowest profits on the average during the entire run when it is unconstrained during the contract case. Fig. 6 shows the effect on the profits for KNBPS under the different scenarios. When KNBPS is constrained during the base case, it also earns higher profits compared to the unconstrained base case, which can give it incentives to operate and offer output on the market which is less than its maximum available capacity. The market regulator, ERB would therefore be required, like in the KGPS case, to assess the true status of the GenCo under this scenario as well. It is also worth mentioning that it would not be in the interest of any of the GenCos to withhold capacity to facilitate higher profits for its competitor unless the GenCos collude. The market regulator, ERB should therefore be wary of such issues and act accordingly to curb them

Fig. 7 shows the LMP trend under the different scenarios at hour 19 from day 5 to 100. It can be observed that the market produces the highest LMPs when KGPS is constrained during the contract case. This observation tallies with the trend in profits for KGPS shown in Figure 9. As expected the lowest average LMPs are observed during the unconstrained base case. The base case and contract case LMPs increase by about 300% and 600% on average respectively when compared with the benchmark LMPs (when GenCos submit true marginal costs).

Overall, KGPS and KNBPS both tend to earn higher profits when KGPS is constrained during the contract case and lower profits when KNBPS is constrained during the contract case. The two scenarios also have the highest average LMP at 14.2 $/MWh and second lowest LMP at 7.5$/MWh respectively.

Table 2: Residual Supply Index (RSI) Values – Base Case

BASE CASE					
Hour	**Total System Load**	**RSI (KGPS)**	**RSI (KNBPS)**	**Station Capacity**	**MW**
0:00	1537.43	0.58815	0.76377	KGPS	990
1:00	1515.28	0.59675	0.77493	KNBPS	720
2:00	1491.19	0.60639	0.78745	VFPS A	8
3:00	1474.21	0.61337	0.79652	VFPS B	60
4:00	1514.43	0.59708	0.77537	VFPS C	40
5:00	1558.31	0.58027	0.75353	LHPC	52.5
6:00	1588.48	0.56925	0.73922	SmallHydros	23.75
7:00	1592.87	0.56768	0.73718	**Total supply**	**1894.25**
8:00	1642.64	0.55048	0.71485		
9:00	1616.04	0.55954	0.72661		
10:00	1561.14	0.57922	0.75217		
11:00	1593.05	0.56762	0.73710		
12:00	1566.578	0.57721	0.74956		
13:00	1536.18	0.58863	0.76439		
14:00	1481.48	0.61036	0.79261		
15:00	1453.24	0.62222	0.80801		
16:00	1509.93	0.59886	0.77768		
17:00	1543.08	0.58600	0.76097		
18:00	1578.53	0.57284	0.74388		
19:00	1666.05	0.54274	0.70480		
20:00	1620.27	0.55808	0.72472		
21:00	1555.62	0.581275	0.75483		
22:00	1534.96	0.589101	0.76500		
23:00	1516.04	0.596452	0.77454		

VI. CONCLUSIONS

The study has shown that GenCos bid in the market with profit maximization as their objective function. It has shown that GenCos subsequently changed their bids in the day-ahead market following the profit results of their earlier bids. The study has also shown that it is possible for KGPS & KNBPS to withhold capacity in order to raise their profits. Regulatory mechanisms need to be in place to ensure that producers do not bid excessively beyond their operating costs.

The Zambian network considered in the study indicates that the market is highly concentrated. The market performance measures calculated, i.e. RSI, RMAI and LI, indicate seller market power by the two largest GenCos, KGPS and KNBPS. The RSI is not greater than 1.1 for 95% of the time for the base case and contract case. The RSI value for the projected generation and forecasted demand case greatly improves and all GenCos except one meet the CAISO threshold indicating that the market is heading towards low concentration.

Despite the prevalence of market exploitation by the two largest GenCos assessed, electricity markets can work in Zambia with strict market rules until such a time the market matures.

The wholesale model (contract case) is recommended for the Zambian market as it will provide the much needed future revenue streams security needed by investors rather than using PPAs. This is coupled with the fact that in hydro systems prices vary seasonally making contracts easier to implement.

REFERENCES

[1] A. Somani and L. Tesfatsion, "An Agent Based Test Bed Study of Wholesale Power Market Performance Measures," *IEEE Computational Intelligence Magazine (,* Vols. 3, No. 4,, pp. 56-72, November, 2008.

[2] P. Vassilopoulos, "Models for the Identification of Market Power in Wholesale Electricity Markets," 2003.

[3] D. Koesrindartoto, J. Sun and L. Tesfatsion, "An Agent-Based Computational Laboratory for Testing the Economic Reliability of Wholesale Power Market Designs," in IEEE Power Engineering Society Conference Proceedings, California, June, 2005.

[4] H. Li, J. Sun and L. Tesfatsion, "Separation and Volatility of Locational Marginal Prices in Restructured Wholesale Power Markets," March, 2010.

[5] L. Tesfatsion, "The AMES Wholesale Power Market Test Bed as a Stochastic Dynamic State-Space Game," August, 2008.

[6] L. Tesfatsion and H. Li, "Capacity Withholding in Restructured Wholesale Power Markets: An Agent-Based Test Bed Study," Seattle, 2009.

[7] L. Tesfatsion and J. Sun, "Dynamic Testing of Wholesale Power Market Designs: An Open-Source Agent-Based Framework," Computational Economics, July, 2007.

[8] L. Tesfatsion and J. Sun, "DC-OPF Formulation with Price-Sensitive Demand Bids," 2008.

[9] L. Tesfatsion and H. Li, "The AMES Wholesale Power Market Test Bed: A Computational Laboratory for Research, Teaching, and Training," in IEEE Power and Energy Society General Meeting, 2009.

[10] J. Mwanza, "Economic Modeling of Hydro Power System Operations," Kathmandu University, Kathmandu, 2010.

[11] R. Bo, "Congestion and Price Prediction in Locational Marginal Pricing Markets Considering Load Variation and Uncertainty," University of Tennessee, Knoxville, 2009.

[12] E. Moyo and F. S. Chanda, "Zambia and Its Small Hydropower Potential," Hangzhou Regional Centre, Hangzhou, China, 2009.

[13] A. Sheffrin, J. Chen and B. Hobbs, "Watching Watts to Prevent Abuse of Power," IEEE Power and Energy Magazine, p. 58–65, July/August 2004.

[14] L. Tesfatsion, "DC Optimal Power Flow Formulation in AMES," 2010.

[15] I. Wangensteen, Power System Economics - the Nordic Electricity Market, Trondheim: Tapir Academic Press, December, 2011.

[16] P. Yangdon, "Modeling and Analysis of a Competitive Electricity Market in Bhutan," Chalmers University, Göteborg, 2009.

[17] T. J. Overbye and J. D. Weber, "An Individual Welfare Maximization Algorithm for Electricity Markets," in IEEE Transactions on Power Systems, August 2002.

[18] L. Tesfatsion and J. Sun, "Open-source software for power industry research, teaching, and training: A DC-OPF illustration," in IEEE Proceedings PES GM, Tampa, Florida,., June, 2007.

Table 3: Residual Supply Index (RSI) Values – Contract Case

CONTRACT CASE							
Hour	**Total System Load**	**RSI (KGPS)**	**RSI (KNBPS)**	**Station Capacity**	**MW**	**Contract**	**Market Supply**
0:00	1537.436549	0.848328	1.023945	KGPS	990	400	590
1:00	1515.288127	0.860727	1.038911	KNBPS	720	400	320
2:00	1491.195524	0.874634	1.055697	VFPS A	8		
3:00	1474.210043	0.884711	1.06786	VFPS B	60		
4:00	1514.433683	0.861213	1.039497	VFPS C	40		
5:00	1558.317209	0.836961	1.010224	LHPC	52.5		
6:00	1588.488337	0.821064	0.991037	SmallHydros	23.75		
7:00	1592.87508	0.818802	0.988307	**Total supply**	**1894.25**		
8:00	1642.649548	0.793992	0.95836				
9:00	1616.045956	0.807062	0.974137				
10:00	1561.142071	0.835446	1.008396				
11:00	1593.051021	0.818712	0.988198				
12:00	1566.578541	0.832547	1.004897				
13:00	1536.184049	0.849019	1.02478				
14:00	1481.487333	0.880365	1.062615				
15:00	1453.248698	0.897472	1.083263				
16:00	1509.939443	0.863776	1.042591				
17:00	1543.086595	0.845222	1.020196				
18:00	1578.535119	0.826241	0.997285				
19:00	1666.0562	0.782837	0.944896				
20:00	1620.276843	0.804955	0.971593				
21:00	1555.62978	0.838406	1.01197				
22:00	1534.963772	0.849694	1.025594				
23:00	1516.046398	0.860297	1.038392				

Table 4: Residual Supply Index (RSI) Values – Forecast Case

	2020 RSI CALCULATION BASED ON CURRENT PROJECTS						
	Projected Peak Load (MW)	**RSI (KGPS)**	**RSI (KNBPS)**	**RSI (KGL)**	**RSI (MAMBA)**	**Station Capacity**	**MW**
Lower Case	**2583**	1.058556	1.163086	1.15147116	1.20954317	KGPS	990
Base Case	**2732**	1.000824	1.099652	1.0886713	1.14357613	KNBPS	720
Upper Case	**3243**	0.843124	0.92638	0.9171292	0.96338267	VFPS A	8
						VFPS B	60
						VFPS C	40
						LHPC	52.5
						SmallHydros	23.75
					Proj. Gen*	ITT	120
					Proj. Gen*	KGL	750
					Proj. Gen*	MAMBA	600
					Proj. Gen*	KNBE	360
						Total supply	**3724.25**

*__Projected Generation__

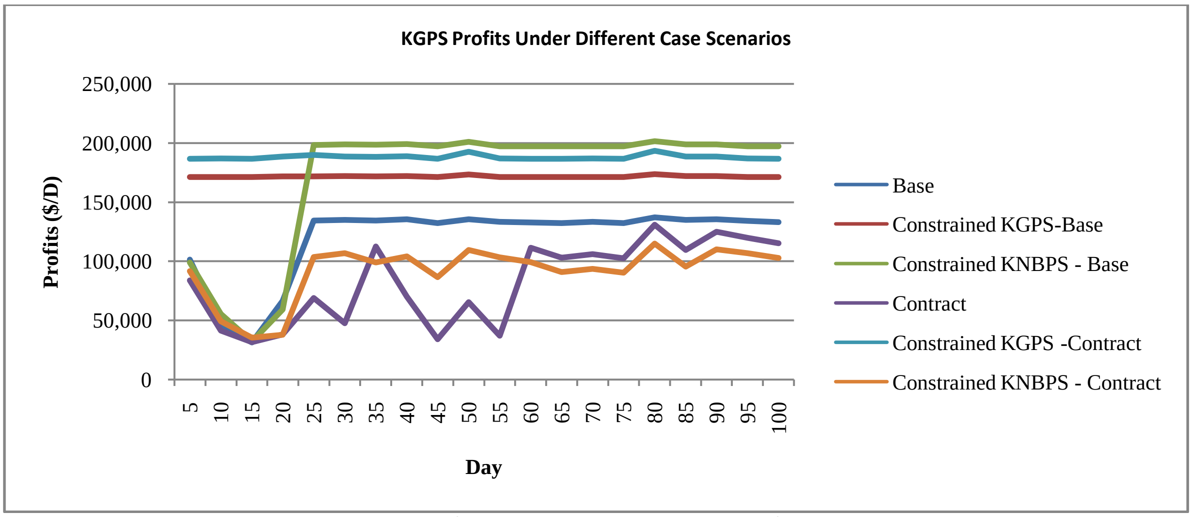

Figure 5: Kafue Gorge Power Station (KGPS) Profit Trends

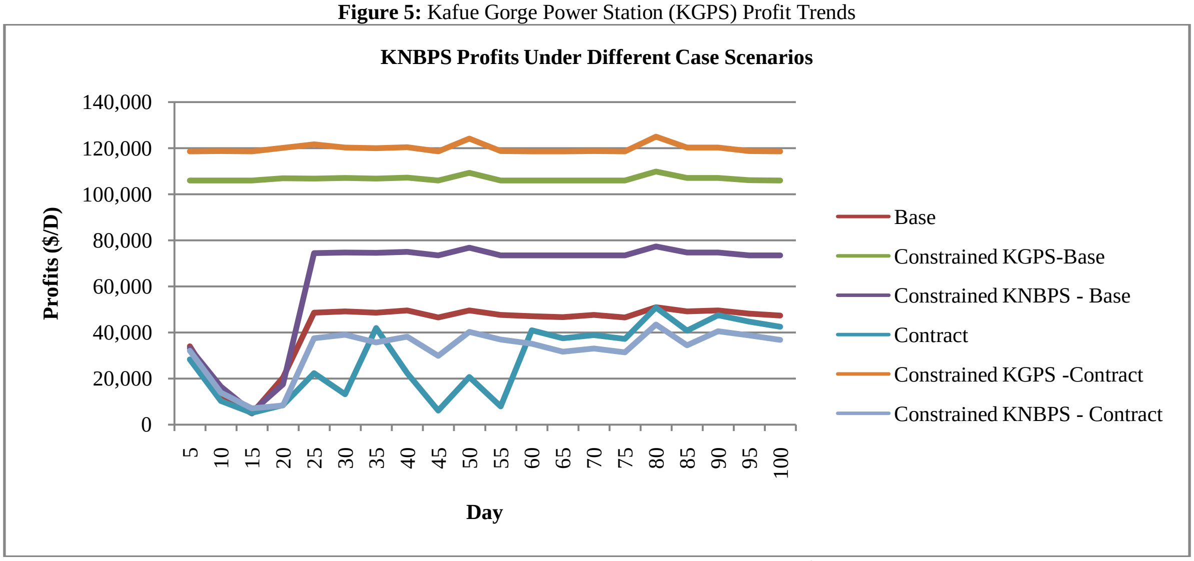

Figure 6: Kariba North Bank Power Station (KNBPS) Profit Trends

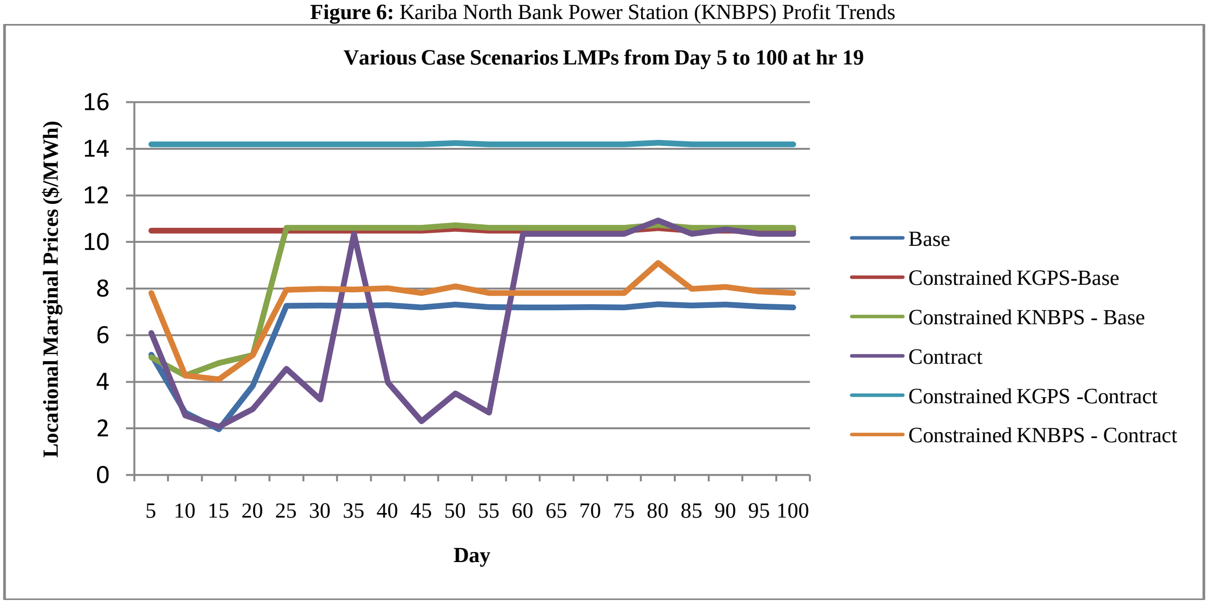

Figure 7: Locational Marginal Prices (LMPs) Trends